International Standard ISO 7919/1

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Mechanical vibration of non-reciprocating machines — Measurements on rotating shafts and evaluation — Part 1 : General guidelines

Vibrations mécaniques des machines non alternatives — Mesurages sur les arbres tournants et évaluation — Partie 1 : Directives générales

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work.

Draft International Standards adopted by the technical committees are circulated to the member bodies for approval before their acceptance as International Standards by the ISO Council. They are approved in accordance with ISO procedures requiring at least 75 % approval by the member bodies voting.

International Standard ISO 7919/1 was prepared by Technical Committee ISO/TC 108, *Mechanical vibration and shock*.

Users should note that all International Standards undergo revision from time to time and that any reference made herein to any other International Standard implies its latest edition, unless otherwise stated.

Mechanical vibration of non-reciprocating machines — Measurements on rotating shafts and evaluation — Part 1 : General guidelines

0 Introduction

Machines are now being operated at increasingly high speeds and loads, and under increasingly severe operating conditions. This has become possible, to a large extent, by the more efficient use of materials, although this has sometimes resulted in there being less margin for design and application errors.

At present, it is not uncommon for continuous operation to be expected and required for 2 or 3 years between maintenance operations. Consequently, more restrictive requirements are being specified for operating vibration levels of rotating machinery, in order to ensure continued safe and reliable operation.

ISO 2372 establishes a basis for the evaluation of mechanical vibration of machines by measuring the vibration response on stationary members only. There are many types of machines, however, for which measurements on structural members, such as the bearing housings, may not adequately characterize the running condition of the machine, although such measurements are useful. Such machines generally contain flexible rotor shaft systems, and changes in the vibration condition may be detected more decisively and more sensitively by measurements on the rotating elements. Machines having relatively stiff and/or heavy casings in comparison to rotor mass are typical of those classes of machines for which shaft vibration measurements are frequently to be preferred.

For machines such as industrial steam turbines, gas turbines, and turbo-compressors, all of which may have several modes of vibration in the service speed range, their responses due to unbalance, thermal bows, rubs, and unloading of bearings, may be more clearly observed by measurements on the shafts.

This International Standard has, therefore, been prepared to complement the guidelines set out in ISO 2372.

Thus, whereas ISO 2372 provides for the measurement of vibration on machine surfaces, such as the bearing caps of bearing housing, this International Standard provides an alternative method for measuring and evaluating those classes of machines the vibration characteristics of which may be more clearly indicated by vibration measurements on their rotating shafts.

Shaft vibration measurements are used for a number of purposes, ranging from routine operational monitoring and acceptance tests to advanced experimental testing, as well as diagnostic and analytical investigations. These various measurement objectives lead to many differences in methods of interpretation and evaluation. To limit the number of these differences, this International Standard is designed to provide guidelines primarily for operational monitoring and acceptance tests.

During the preparation of this International Standard, it was recognized that there was a need to establish quantitative criteria for the evaluation of machinery shaft vibration. However, there is a significant lack of data on this subject at present and, consequently, this International Standard has been structured to allow such data to be incorporated as it becomes available.

NOTES

1 The term "shaft vibration" is used throughout this International Standard because, in most cases, measurements will be made on machine shafts; however, this International Standard is also applicable to measurements made on other rotating elements if such elements are found to be more suitable, provided that the guidelines are respected.

2 For the purposes of this International Standard, operational monitoring is considered to be those vibration measurements made during the normal operation of a machine. This International Standard permits the use of several different measurement quantities and methods, provided that they are well defined and their limitations are set out, so that the interpretation of the measurements will be well understood.

1 Scope and field of application

This part of ISO 7919 sets out general guidelines for measuring and evaluating machinery vibration by means of measurements made directly on rotating shafts for the purpose of determining shaft vibration with regard to

a) changes in vibrational behaviour;

b) excessive kinetic load;

c) the monitoring of radial clearances.

It is applicable to measurements of both absolute and relative radial shaft vibrations, but excludes torsional and axial shaft vibrations. The procedures are applicable for both operational monitoring of machines and to acceptance testing on a test stand and after installation.

NOTE — Evaluation criteria for different classes of machinery will be included in other parts of this International Standard when they become available. In the meantime, guidelines are given, for information only, in annex C.

This International Standard does not apply to reciprocating machinery.

2 References

ISO 2041, *Vibration and shock — Vocabulary.*

ISO 2372, *Mechanical vibration of machines with operating speeds from* 10 *to* 200 rev/s — *Basis for specifying evaluation standards.*

ISO 3945, *Mechanical vibration of large rotating machines with speed range from* 10 *to* 200 rev/s — *Measurement and evaluation of vibration severity* in situ.

ISO 5348, *Mechanical vibration and shock — Mechanical mounting of accelerometers.*[1]

3 Measurements

3.1 Measurement quantities

3.1.1 Displacement

The preferred measurement quantity for the measurement of shaft vibration is displacement. The unit of measurement is the micrometer (1 µm = 10^{-6} m).

NOTE — Displacement is a vector quantity and, therefore, when comparing two displacements, it may be necessary to consider the phase angle between them (see also annex C).

Since this International Standard applies to both relative and absolute shaft vibration measurements, displacement is further defined as follows :

a) relative displacement, which is the vibratory displacement between the shaft and appropriate structure, such as a bearing housing or machine casing; or

b) absolute displacement, which is the vibratory displacement of the shaft with reference to an inertial reference system.

NOTE — It should be clearly indicated whether displacement values are relative or absolute.

Absolute and relative displacement are further defined by several different displacement quantities, each of which is now in widespread use. These include

$S_{\text{p-p}}$: vibratory displacement peak-to-peak in the direction of measurement;

$S_{\max}$: maximum vibratory displacement in the plane of measurement.

Each of these displacement quantities may be used for measurement of shaft vibration; however, the quantities shall be clearly identified so as to ensure correct interpretation of the measurements in terms of the criteria of clause 5. The relationship between each of these quantities are shown in the figures in annex A.

NOTE — At present, the greater of the two values for peak-to-peak displacement, as measured in two orthogonal directions, is used for evaluation criteria. In future, as relevant experience is accumulated, the quantity $S_{\text{p-p}_{\max}}$, defined in figure 2 in annex A, may be preferred.

3.1.2 Frequency range

The measurement of relative and absolute shaft vibration shall be broad band so that the frequency spectrum of the machine is adequately covered.

3.2 Types of measurement

3.2.1 Relative vibration measurements

Relative vibration measurements are generally carried out with a non-contacting transducer which senses the vibratory displacement between the shaft and a structural member (e.g. the bearing housing) of the machine.

3.2.2 Absolute vibration measurements

Absolute vibration measurements are carried out by one of the following methods :

a) by a shaft-riding probe, on which a seismic transducer (velocity type or accelerometer) is mounted so that it measures absolute shaft vibration directly; or

b) by a non-contacting transducer in combination with a seismic tranducer (velocity type or accelerometer), mounted close together so that the support structure of both transducers undergoes the same absolute motion in the direction of measurement. Their conditioned outputs are vectorially summed to provide a measurement of the absolute shaft motion.

1) At present at the stage of draft.

3.3 Measurement procedures

3.3.1 General

It is desirable to locate transducers at positions such that the lateral movement of the shaft at points of importance can be assessed. It is recommended that, for both relative and absolute measurements, two transducers should be located at, or adjacent to, each machine bearing. They should be radially mounted in the same transverse plane perpendicular to the shaft axis or as close as practicable, with their axes within ± 5° of a radial line. It is preferable to mount both transducers 90 ± 5° apart on the same bearing half and the positions chosen should be the same at each bearing.

A single transducer may be used if it can be shown that it provides adequate information about the shaft vibration characteristics.

It is recommended that special measurements be made in order to determine the total non-vibration run-out, which is caused by shaft surface metallurgical non-homogeneities, local residual magnetism and shaft mechanical run-out. It should be noted that, for asymmetric rotors, the effect of gravity can cause a false run-out signal.

Recommendations for instrumentation are given in annex B.

3.3.2 Procedures for relative vibration measurements

Relative vibration transducers of the non-contacting type are normally mounted in tapped holes in the bearing housing, or by rigid brackets adjacent to the bearing housing. Where the transducers are mounted in the bearing, they should be located so as not to interfere with the lubrication pressure wedge. However, special arrangements for mounting transducers in other axial locations may be made, but different vibration criteria for assessment will then have to be used. For bracket-mounted transducers, the bracket shall be free from natural frequencies which adversely affect the capability of the transducer to measure the relative shaft vibration.

The surface of the shaft at the location of the pick-up, taking into account the total axial float of the shaft under all thermal conditions, shall be smooth and free from any geometric discontinuities, such as keyways, lubrication passages and threads, metallurgical non-homogeneities and local residual magnetism which may cause false signals. In some circumstances, an electroplated or metallized shaft surface may be acceptable, but it should be noted that the calibration may be different. It is recommended that the total combined electrical and mechanical run-out, as measured by the transducer, should not exceed 25 % of the allowable vibration displacement, specified in accordance with annex C, or 6 μm, whichever is the greater. For measurements made on machines already in service, where provision was not originally made for shaft vibration measurements, other run-out criteria may need to be used.

3.3.3 Procedures for absolute vibration measurements using combined seismic and non-contacting relative vibration transducers

If a combination of seismic and non-contacting relative vibration transducers are used, the absolute vibration is obtained by vectorially summing the outputs from both transducers. The mounting and other requirements for the non-contacting transducer are as specified in 3.3.2. In addition, the seismic tranducer shall be rigidly mounted to the machine structure (e.g. the bearing housing) close to the non-contact transducer so that both transducers undergo the same absolute vibration of the support structure in the direction of measurement. The sensitive axes of the non-contact and seismic transducers shall be parallel, so that their vectorially summed, conditioned signals result in an accurate measure of the absolute shaft vibration.

3.3.4 Procedures for absolute vibration measurements using a shaft-riding mechanism with a seismic transducer

The seismic transducer (velocity type or accelerometer) shall be mounted radially on the shaft-riding mechanism. The mechanism shall not chatter or bind in a manner modifying the indicated shaft vibrations. The mechanism shall be mounted as described for transducers in 3.3.1.

The shaft surface against which the shaft-riding tip rides, taking into account the total axial float of the shaft under all thermal conditions, shall be smooth and free from shaft discontinuities, such as keyways and threads. It is recommended that the mechanical run-out of the shaft, as measured with a dial indicator of suitable resolution, should not exceed 25 % of the allowable vibration displacement, specified in accordance with annex C, or 6 μm, whichever is the greater.

There may be surface speed and/or other limitations to shaft-riding procedures, such as the formation of hydrodynamic oil films beneath the probe, which may give false readings, and, consequently, manufacturers should be consulted about possible limitations.

3.4 Machine operating conditions

Shaft vibration measurements should be made under agreed conditions over the operating range of the machine. These measurements should be made after achieving agreed thermal and operating conditions. In addition, measurements may also be taken under conditions of, for example, slow roll, warming-up speed, critical speed, etc; however, the results of these measurements may not be suitable for evaluation in accordance with clause 5.

3.5 Machine foundation and structures

The type of machine foundation and structures (for example piping) may significantly affect the measured vibrations. In general, a valid comparison of vibration levels of machines of the same type can only be made if the foundations and structures have similar dynamic characteristics.

3.6 Environmental vibration and evaluation of measurement system

Prior to measuring the vibration of an operating machine, a check with the same measuring system and stations should be taken with the machine in an inoperative state. When the results of such measurements exceed one-third of the values specified for the operating speed, steps should be taken to eliminate environmental vibration effects.

4 Instrumentation

The instrumentation used for the purpose of compliance with this part of ISO 7919 shall be so designed as to take into account temperature, humidity, the presence of a corrosive atmosphere, shaft surface speed, shaft material and surface finish, operating medium (for example water, oil, air or steam) in contact with the transducer, vibration and shock (three major axes), airborne noise, magnetic fields, metallic masses in proximity to the tip of the transducer, and power-line voltage fluctuations and transients.

The design of the measurement system and the individual components shall also be such that, for a given application over the maximum range of environmental conditions, the measurement error of the system shall not exceed 10 % of the measured value or 10 % of the two-thirds value of the read-out instrument, whichever is the greater.

The instrumentation shall have provision for on-line calibration of read-out instrumentation. It is desirable to have suitable isolated outputs to permit further analysis if required. Annex B provides examples of instrumentation used for relative and absolute shaft vibration measurements.

5 Evaluation criteria

5.1 There are two principal factors by which shaft vibration is judged

a) absolute vibration of the shaft;

b) vibration of the shaft relative to the structural elements.

5.2 If the evaluation criterion is the change in shaft vibration, then

a) when the relative motion transducer support structure vibration is small (i.e. less than 20 % of the relative shaft vibration), either the relative shaft vibration or absolute shaft vibration may be used as a measure of shaft vibration;

b) when the relative motion transducer support structure vibration is 20 % or more of the relative shaft vibration, the absolute shaft vibration shall be measured, and if found to be larger than the relative shaft vibration, it shall be used as the measure of shaft vibration.

5.3 If the evaluation criterion is the kinetic load on the bearing, the relative shaft vibration shall be used as the measure of shaft vibration.

5.4 If the evaluation criterion is stator/rotor clearances, then

a) when the relative motion transducer support structure vibration is small (i.e. less than 20 % of the relative shaft vibration), the relative shaft vibration shall be used as a measure of clearance absorption;

b) when the relative motion transducer support structure vibration is 20 % or more of the relative shaft vibration, the relative shaft vibration measurement may still be used as a measure of clearance absorption unless the relative motion transducer support structure vibration is not representative of the total stator vibration. In this latter case, special measurements will be required.

5.5 The shaft vibration associated with a particular classification range depends on the size and mass of the vibrating body, the characteristics of the mounting system and the output and use of the machine. It is therefore necessary to take into account the various purposes and circumstances concerned when specifying different ranges of shaft vibration for a specific class of machinery. Where appropriate, reference should be made to the product specification.

Annex A

Derivation of measurement quantities

(This annex does not form an integral part of the standard.)

A.1 Mechanics of shaft vibration

The vibration of a rotating shaft is characterized at any axial location by a kinetic orbit, which describes how the position of the shaft centre varies with time. Figure 1 shows a typical orbit. The shape of the orbit depends upon the dynamic characteristics of the shaft, the bearings and the bearing supports/foundations, the axial location on the rotor and the form of vibration excitation. For example, if the excitation takes the form of a single frequency sinusoidal force, the orbit is an ellipse, which can in certain circumstances be a circle or straight line, and the time taken for the shaft centre to complete one circuit of the ellipse is equal to the period of the excitation force. One of the most important excitation forces is rotor unbalance, in which the excitation frequency is equal to the rotational frequency of the shaft. However, there are other forms of excitation, such as rotor cross-section asymmetry, for which the frequency is equal to multiples of the rotational frequency of the shaft. Where the vibration arises as a result of, for example, destabilizing self-excited forces, the orbit will not normally be of a simple shape, but will change form over a period of time and it will not necessarily be harmonically related. In general, the vibration of the shaft may arise from a number of different sources and, therefore, a complex orbit will be produced, which is the vectorial sum of the effects of the individual excitation forces.

A.2 Measurement of shaft vibration

At any axial location, the orbit of the shaft can be obtained by taking measurements with two vibration transducers mounted in different radial planes, separated by 90° (this is the preferred separation, but small deviations from this do not cause significant errors). If the angle between the transducer locations is substantially different from 90°, a vector resolution into the orthogonal directions will be required. If the transducers measure absolute vibration, then the orbit will be the absolute orbit of the shaft independent of the vibratory motion of the non-rotating parts. If the transducers measure relative vibration, then the measured orbit will be relative to that part of the structure upon which the transducers are mounted.

A.3 Measurement quantities

A.3.1 Time-integrated mean position

The mean values of the shaft displacement ($\bar{x}$, $\bar{y}$), in any two specified orthogonal directions, relative to a reference position, as shown in figure 1, are defined by integrals with respect to time, as shown in the following equations :

$$\bar{x} = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} x(t)\,\mathrm{d}t \qquad \ldots (1)$$

$$\bar{y} = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} y(t)\,\mathrm{d}t \qquad \ldots (2)$$

where $x(t)$ and $y(t)$ are the time-dependent alternating values of displacement relative to the reference position, and $(t_2 - t_1)$ is large relative to the period of the lowest frequency vibration component. In the case of absolute vibration measurements, the reference position is fixed in space. For relative vibration measurements, these values give an indication of the mean position of the shaft relative to the non-rotating parts at the axial location where the measurements are made. Changes in the values may be due to a number of factors, such as bearing/foundation movements, changes in oil film characteristics, etc., which normally occur slowly relative to the period of the vibration components which make up the alternating values.

It should be noted that the time-integrated mean position in any direction differs from the position defined by taking half the summation of the maximum and minimum displacement values (see figure 2). However, when the shaft vibration is a single frequency and sinusoidal, then the locus of the shaft centre will be an ellipse. In such circumstances, the time-integrated mean position in any direction of measurement will be the same as the position identified by taking half the summation of the maximum and minimum displacement values.

A.3.2 Vibration peak-to-peak displacement

The primary quantities of interest in shaft measurements are the alternating values which describe the shape of the orbit. Consider the kinetic shaft orbit shown in figure 2 and assume that there are two transducers A and B mounted 90° apart, which are used to measure the shaft vibration. At some instant, the shaft centre will be coincident with the point K on the orbit and the corresponding instantaneous value of shaft displacement from the mean position will be S_1. However, in the plane of the transducers A and B, the instantaneous values of shaft displacement from the mean position will be S_{A1} and S_{B1}, respectively, where

$$S_1^2 = S_{A1}^2 + S_{B1}^2 \qquad \dots (3)$$

The values of S_1, S_{A1} and S_{B1} will vary with time as the shaft centre moves around the orbit; the corresponding waveforms measured by each transducer are shown in figure 2.

NOTE — If the orbit is elliptical, then these waveforms would be pure sine waves of the same frequency.

The peak-to-peak value of the displacement in the plane of transducer A (S_A peak-to-peak) is defined as the difference between the maximum and minimum displacements of transducer A and similarly for S_B for transducer B. Clearly S_A peak-to-peak and S_B peak-to-peak values will not be equal, and, in general, they will be different from similar measurements made in other radial directions. Hence, the value of the peak-to-peak displacement is dependent on the direction of the measurement.

Since these measurement quantities are independent of the absolute value of the mean position, it is not necessary to use systems which can measure both the mean and alternating values.

Peak-to-peak displacement is the unit which has been used most frequently for monitoring vibration of rotating machines.

Whereas measurement of the peak-to-peak displacement in any two given orthogonal directions is a simple matter, the value and angular position of the maximum peak-to-peak displacement shown in figure 2 is difficult to derive. However, in practice, it has been found acceptable to use alternative measurement quantities which enable a suitable approximation for the maximum peak-to-peak displacement value to be obtained. For more precise determinations, it is necessary to examine the shaft orbit in more detail, as for example with an oscilloscope. The three most common methods for obtaining satisfactory approximations are described in A.3.2.1 to A.3.2.3.

A.3.2.1 Method A : Resultant value of the peak-to-peak displacement values measured in two orthogonal directions

The value of $S_{p\text{-}p_{max}}$ can be approximated from the following equation :

$$S_{p\text{-}p_{max}} = \sqrt{(S_{A_{p\text{-}p}})^2 + (S_{B_{p\text{-}p}})^2} \qquad \dots (4)$$

The use of equation (4) as an approximation when the vibration is predominantly at synchronous frequency will generally over-estimate the value of $S_{p\text{-}p_{max}}$ with a maximum error of approximately 40 %.

The maximum error occurs for a cicular orbit and progressively reduces as the orbit becomes flatter, with a zero error for the degenerate case of a straight line orbit.

A.3.2.2 Method B : Taking the maximum value of the peak-to-peak displacement values measured in two orthogonal directions

The value of $S_{p\text{-}p_{max}}$ can be approximated from the following equation :

$$S_{p\text{-}p_{max}} = S_{A_{p\text{-}p}} \text{ or } S_{B_{p\text{-}p}}, \text{ whichever if the greater.} \qquad \dots (5)$$

The use of equation (5) as an approximation when the vibration is predominantly at synchronous frequency will generally under-estimate the value of $S_{p\text{-}p_{max}}$ with a maximum error of approximately 30 %.

The maximum error occurs for a flat orbit and progressively reduces as the orbit becomes circular, with a zero error when the orbit is circular.

A.3.2.3 Method C : Measurement of S_{max}

The instantaneous value of shaft displacement can be defined by S_1, as shown in figure 2, which is derived from the transducer measurements S_{A1} and S_{B1} using equation (3). There is a point on the orbit, defined by point P in figure 3 where the displacement from the mean position is a maximum. The value of S_1 corresponding to this position is denoted by S_{max}, which is defined as the maximum value of displacement.

$$S_{max} = [S_1 (t)]_{max} = \left[\sqrt{[S_A (t)]^2 + [S_B (t)]^2} \right]_{max} \qquad \ldots (6)$$

The point on the orbit where S_{max} occurs does not necessarily coincide with the points where S_A and S_B are at their maximum values. Clearly, for a particular orbit, there is one value of S_{max} and this is independent of the position of the measuring transducers.

The value of $S_{p\text{-}p_{max}}$ can be approximated from the following equation :

$$S_{p\text{-}p_{max}} = 2\, S_{max} \qquad \ldots (7)$$

Equation (7) will be correct when the two orthogonal measurements from which S_{max} is derived are of single frequency sinusoidal form. In most other cases, this equation will over-estimate $S_{p\text{-}p_{max}}$, this depending on the nature of the harmonic vibration components present.

It should be noted that implicit in the definition of S_{max} is the requirement to know the time integrated mean value of the shaft displacement. The measurement of S_{max} is, therefore, limited to those measuring systems which can measure both the mean and alternating values. Furthermore, the evaluation of S_{max} from the signals produced by two vibration transducers is a relatively complex computational procedure requiring specialized instrumentation.